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A RELIABILITY CENTERED MAINTENANCE ANALYSIS OF AIRCRAFT CONTROL BEARINGS USED IN THE NAVY'S S-3 AIRCRAFT

by

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In our research, we analyzed and established a historical bearing failure data baseline of current reliability and maintenance costs. We developed a mathematical model to determine the effects of using improved bearings, currently available from commercial manufacturers, on bearing reliability and life cycle costs. We show that failure rates can be reduced by 50 percent, and maintenance costs can be reduced by 48 percent, which represents $16,000 in annual savings over the remaining life of the aircraft.

We show that an increase in bearing and flight control system reliability is important from the aspect of aircrew safety, and reduces the exposure of aircrews to the potential of in-flight failures.

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This thesis uses the Naval Air Systems Command Integrated Reliability Centered Maintenance Program software (IRCMS) to analyze the performance of aircraft control bearings used in the flight control system of the Navy's S-3 aircraft. The IRCMS is used to determine whether changes can be made in preventative maintenance prorcedures, or if redesign of the system is warranted. We show in our analysis that each bearing should be redesigned.

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I. INTRODUCTION

A. Background

This research will identify and analyze those hardware components in the S-3 aircraft's flight control systems that are degrading system readiness and reliability. This will be accomplished using the Naval Air Systems Command's (NAVAIR) version of Reliability Centered Maintenance (RCM) software, Integrated Reliability Centered Maintenance Software (IRCMS). IRCMS is a tool for performing and documenting a RCM analysis.

A statistical analysis of historical failure data is also performed, and an optimum maintenance plan, using components manufactured with advanced processes, is developed for the components identified.

B. Objectives

The objectives of this thesis is to utilize NAVAIR's RCM program and statistical analysis to identify readiness degraders, and improve the reliability of the flight control system through either optimized preventative maintenance, or utilization of improved components. Through use of RCM and statistical analysis, components with poor reliability can be identified, and cost/benefit tradeoffs can be accomplished in order to seek optimal solutions to achieving increased reliability.

C. Research Questions

The thesis will answer the following questions:

1. What is RCM, and how is it used to improve system readiness?

2. How is Integrated Reliability Centered Maintenance Software (IRCMS) utilized to analyze data?
3. What are the top readiness degraders of the S-3's flight control system?
4. How are these degraders impacting maintenance?
5. Is there preventative maintenance (PM) established for these components, and is this preventative maintenance effective?
6. What are the failure modes of the degraders? What factors contribute to failures?
7. Can reliability of the system be improved through changes in scheduled maintenance, an optimized maintenance plan, or replacement of the components?
8. What is the cost/benefits of the analysis output?

D. Scope, Limitations, and Methodology

The scope will include: (1) identifying the top readiness degraders of the S-3 aircraft's flight control components, (2) an analysis of those components using NAVAIR's IRCMS software, (3) developing an optimum maintenance plan that minimizes total expenses, (4) impact of the components on life cycle maintenance costs, and (5) an analysis of current preventative maintenance procedures that apply to the components discussed. The thesis will conclude with recommendations to improve system reliability.

The methodology used in this thesis research will consist of the following steps:

1. Conduct a data base search of aviation maintenance data (AV-3M) from the Naval Aviation Maintenance Office, and cognizant field activity (CFA) data

from the Naval Aviation Depot (NADEP) at North Island, Ca., to identify what flight control components are suiTable for RCM analysis.

2. Using NAVAIR's IRCMS software, analyze the components to determine failure modes, and causal factors.
3. Research current maintenance requirements for applicability to the selected components.
4. Determine environmental exposure of selected components by inspecting component location on the aircraft.
5. Through interviews with maintenance personnel from VS-41, the S-3 Fleet Replacement Squadron (FRS) at NAS North Island, determine maintenance times required to remove and replace the selected components.
6. Using reliability models, determine the availability probabilites for the components.

E. Organization of the Study

Chapter II describes NAVAIR's RCM program structure, and provides the basis for the thesis study. Chapter III provides and explanation of assumtions used to develop the RCM analysis. In Chapter IV, the components that will be analyzed are identified. In Chapter V, the IRCMS program is used to determine a course of action. In chapter VI, a statistical model is developed to show historical maintenance costs, and the effect on costs if improved components are used. Chapter VII presents conclusions and recommendations.

II. NAVAIR's RCM PROGRAM

A. Introduction

Reliability: The probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operation conditions [Ref. 1: p 14].

Reliability Centered Maintenance was developed in the United States in the early 1960's, by the civilian aviation industry. It was developed when airline companies realized that their maintenance philosophies were not only expensive, but dangerous as well. This realization prompted the industry to put together a series of "Maintenance Steering Groups" (MSG) to reexamine all processes related to aviation maintenance practices. These groups consisted of representatives from aircraft manufacturers, the airlines, and the FAA.

The first attempt at formulating maintenance strategies was promulgated by the Air Transport Association in Washington, DC, in 1968. This first attempt is known as MSG1. The first revision, MSG2, was issued in 1970. In the mid 1970's, the Department of Defense desired to improve its maintenance practices, and commissioned a report on the subject from the aviation industry. Stanley Nowlan and Howard Heap of United Airlines wrote this report. They titled it "Reliability Centered Maintenance". [Ref 2] The report was published in 1978, and is considered to be one of the most important documents in physical asset management.

Nowlan and Heap's report represented a considerable advance on MSG2 thinking. It was used as the basis for MSG3, which was released in 1980. MSG3 has been since revised twice. Revision 1 was issued in 1988, and Revision 2 in 1993. It is used today to develop prior to service maintenance programs for new aircraft types (recently Boeing's 777, and Airbus' 330/340).

B. Program Overview

The Naval Air Systems Command version of RCM was developed from MSG1 and MSG2, modified to the Analytical Maintenance Program, and then to the present RCM program, encompassing RCM analysis and Age Exploration (AE) analysis. NAVAIR's current directive on RCM is the NAVAIR 4790.20. This instruction describes policy, procedures, and responsibilities for application of RCM analysis for systems under NAVAIR cognizance [Ref 3]. The RCM program is applied in three basic stages:

1) To influence design guidelines and equipment design.
2) To develop a preventative maintenance (PM) program encompassing all levels of maintenance.
3) To continually review and update preventative maintenance requirements throughout the life cycle of the equipment.

NAVAIR's RCM program is applicable to new procurement and in-service aircraft, airborne weapons systems, and support equipment. The program includes establishing priorities during concept and design to influence preventative maintenance requirements. NAVAIR's RCM management manual, the NAVAIR 00-25-403, provides guidance on performing the RCM analysis, implementation of results, and sustaining efforts.

NAVAIR's current version of IRCMS, version 5.3.1, is used to perform all NAVAIR RCM analyses [Ref 4: p 1-1].

C. NAVAIR RCM Program Planning

Development of a RCM program is the first of many steps in initiating a program that maximizes safety and operation availability, reduces overall costs of ownership, achieves equipment inherent availability, and provides an audit trail for PM requirements. The RCM program plan describes all processes and procedures that are performed as part of the analysis effort. The following are elements of NAVAIR's RCM program [Ref. 4: p. 2-1]:

1. RCM analysis ground rules and assumptions
2. Scope of initial analysis
3. Sustaining task procedures
4. Available resources/data identification
5. Responsibilities definition
6. Effectiveness metrics
7. Training requirements
8. Contractor support/interface
9. RCM/LSAR interface
10. Reporting requirements
11. Funding requirements
12. RCM program plan of action and milestones (POA&M).

This RCM study of the S-3's flight control components will be limited to addressing items 1, 2, 3, and 6 [1]. Each of the four items will be discussed in detail, in Chapter III.

[1] These four areas constitute the minimum areas needed to start this RCM analysis.

III. THE RCM ANALYSIS PROCESS

A. Introduction

Of the twelve RCM elements, four have been determined to be fundamental in performing this study:

1. Ground rules and assumptions
2. Scope of the initial analysis
3. Sustaining tasks
4. Effectiveness metrics

It is here that the foundations of the analysis are determined. Specific examples of types of ground rules and lessons learned that have been used in other programs are provided in Appendix 1 of the RCM Management Manual [Ref 3]. All assumptions made in developing this RCM analysis are the author's.

B. RCM Analysis Ground Rules & Assumptions

One of the most important elements in performing and RCM analysis is the establishment of ground rules and assumptions. In establishing ground rules and assumptions for this analysis, four factors are of significant importance: (1) failure mode effects criticality analysis (FMECA), (2) the analysis approach to be used, (3) significant item selection, and (4) preventative maintenance (PM) requirements. Standard operating procedures, data sources, analytical methods, cost benefit analysis methods, specific analysis approach information, default values, and any other appropriate information that is required for a consistent and efficient RCM analysis effort, are identified.

1. Failure Mode Effects Critically Analysis (FMECA)

The FMECA is one of the major data inputs to, and is the starting point of, the RCM process. FMEA attempts to predict possible sequences of events that lead to system failure, determine their consequences, and devise methods to minimize their occurrence [Ref. 5: p 163]. Criticality Analysis enables the determination of the occurrence of the failure modes, and the determination of the impact of a failure mode on the reliability of the system. As such, ground rules & assumptions should also be included for the FMECA unless previously documented elsewhere such as in a FMECA Plan. A FMECA will not be done for this study, as failure modes for the components have been identified by use of malfunction codes documented in NALDA/3M data.[2]

2. Analysis Approach

The analysis approach to be used during the performance of the RCM analysis is a critical element in the planning and executing process. The analysis approach is primarily applicable to the FMECA, which in turn influences the RCM analysis. There are two primary approaches for accomplishing the FMECA/RCM analysis. One is the hardware approach and the other is the functional approach. The following provides a brief description of each approach.

a. Hardware Approach

The hardware approach is normally used when hardware items (such as bearings and control cables), can be uniquely identified from schematics, drawings,

[2] Although IRCMS can perform a FMECA, the assumption is that failure modes have been identified at the time the component was replaced, and each mode is considered to be critical.

maintenance manuals, and other engineering design data. The hardware approach is normally utilized in a part level up fashion (increasing indenture levels/bottom-up approach); however, it can be initiated at any level of indenture and progress in either direction. Each identified failure mode is assigned a severity classification, which is utilized to establish priorities for PM task development or redesign.[3]

b. Functional Approach

The functional approach is normally used when hardware items cannot be uniquely identified or when system complexity requires analysis from the initial indenture level downward through succeeding indenture levels. The functional approach is normally utilized in an initial indenture level down fashion (top-down approach); however, it can be initiated at any level of indenture and progress in either direction. Each identified failure mode is assigned a severity classification, which is utilized to establish priorities for PM task development or redesign.

3. Significant Item (SI) Selection

For this study, SI is defined as a flight control hardware component averaging more than two failures over a seven-year period. This allows for identification and analysis of the components with the highest failure rates. The IRCMS significant item selection logic will be discussed in detail, in chapter IV.

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[3] For this study, the hardware approach will be used since drawings and maintenance manuals readily identify all the components.

4. Directed PM Requirements

Different components may have different levels of maintenance assigned due to the level effort required to accomplish a given maintenance effort. For the organizational level of maintenance, the NAVAIR 01S3AAB-4 instruction details the specific PM requirements that can be performed. At the depot level, PM requirements are identified in the Standard Depot Level Maintenance Specification (NAVAIR S-3SDLM) for the S-3 aircraft.

C. Scope of Initial Analysis

This element of the process defines the scope of the initial analysis. The scope is the amount of initial analysis to be performed and will determine the method of analysis used, and the resources required to complete the tasks [Ref. 4: p 2-6]. The scope of the analysis will differ according to the phase of the program (new acquisition or in-service), and the extent and currency of any prior RCM analysis. As the S-3 is an in-service aircraft, the analysis will address only this phase.

1. In-service Programs - Factors

Many factors are involved in defining the scope for in-service programs. These factors include, but are not limited to, the following:

1. Age of aircraft (life cycle phase)
2. Prior or existing RCM analysis
3. Current maintenance philosophies
4. Number and complexity of aircraft systems

2. In-service Programs - Plan Steps

In determining the scope of analysis for this thesis, the following steps were considered relevant to the analysis:

a. Current PM Program Baseline

The current PM program baseline defines the existing PM tasks. The current version of the S-3's Maintenance Requirements Cards (MRC)[4] is the S3ABB-4, for organizational level PM. The SDLM spec is the NAVAIR S-3SDLM. Any PM actions on the hardware components are accomplished under the guidelines of one of these two directives.

b. RCM Candidate Identification and Prioritization

Identifies functions, items, and/or PM tasks to determine which will be subject to RCM analysis. Prioritizes those that are subject to RCM analysis based on safety, operational availability, and expected return on investment considerations.

3. Scope Definition

The scope of the initial analysis can be limited by using four methods:

1. Stake-in-the-ground method

This is a minimum initial effort method. It assumes most current PM tasks are reasonably justified, and will immediately go into the sustaining phase. Any benefits from RCM will be via proactive sustaining efforts.

2. High profile analysis

This is similar to analysis method one above, which consists of jumping into proactive efforts of the sustaining phase, such as analyzing high cost drivers except that a higher initial effort may be warranted.

3. Back-fill method

This is a medium level effort for the initial analysis. It assumes that the current PM program adequately covers all potential failure modes, but that there may be some PM being performed that may not be required. A list of items and/or functions is developed for analysis from existing PM tasks.

4. Complete analysis

This requires the highest initial effort and should be only considered when potential returns are high, i.e. programs with significant life remaining, and/or high current maintenance costs, and/or very low reliability.

D. Sustaining Tasks

Sustaining tasks enable continued improvement and refinement of the RCM effort. The RCM effort can be addressed from two perspectives categorized as either proactive or reactive. The objective of the proactive analysis is to optimize current PM requirements, delete unnecessary requirements, predict adverse failure trends, predict previously unforeseen failure modes, and improve the overall efficiency and

---

[4] MRCs describe preventative maintenance requirements performed by organizational level personnel.

effectiveness of the RCM/PM program [Ref. 4: p 2-9]. This thesis will use the proactive approach in order to satisfy the objectives of the study. A number of analysis processes are used to meet these objectives:

1. Age Exploration (AE) Tasks

Specific AE tasks (or inspections) are implemented where default answers are used in the initial or updated RCM analysis. These inspections are intended to be of limited duration to provide data which will verify or correct the default answers. The RCM analysis will provide the requirements for specific AE inspections. The RCM/AE Plan provides guidance for the implementation of these AE inspections[5].

2. Top Degrader Analysis

Top degrader ranking indicates which systems or items are having the highest operational or cost impact on the aircraft. Degrader measurement factors could include: maintenance man-hours per flight hour, nonmission capable (NMC) rates, maintenance actions per flight hour, failure rates per flight hour, failure aborts per flight hour, engine caused aborts per flight hour, etc.

3. Preventive Maintenance (PM) Document Reviews

PM documents include Maintenance Requirements Cards (MRCs), depot level maintenance specifications, and any other technical manuals or data, which contain PM requirements. Periodic review of these documents will reveal outdated maintenance

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[5] Although referred to as AE "inspections", they are normally reviews of databases, etc.

processes, techniques, tools, or supplies, allowing updating to increase effectiveness or lower cost.

D. Effectiveness Metrics

One of the goals of RCM analysis is to provide metrics for effectiveness. Types of metrics are cost avoidances, PM man-hours relative to corrective maintenance man-hours, end item availability, etc. Effectiveness metrics for this study are minimizing flight control system downtime resulting from corrective maintenance applied towards the components identified, and accomplishing this cost effectively.

E. Summary

The items selected for this study will be analyzed using the hardware approach. The scope of the analysis will follow the "stake in the ground" method, and will be proactive in nature.

IV. HARDWARE COMPONENTS

A. Introduction

In selecting to analyze hardware components of the S-3's flight control system the intent is to identify those components exhibiting low Mean Time Between Failures (MTBF), and high organizational level maintenance man-hour to unit cost ratios. Annual repair costs (material and man-hour utilization) are two other metrics that will be determined.

MTBF is a significant factor in system availability and supportability, and the frequency of maintenance for a given item is highly dependent on the reliability of that item. As reliability increases the frequency of maintenance and the associated cost of that maintenance will decrease [Ref.1: p. 27]. By increasing reliability of hardware components, such as those used throughout the flight control system, the reliability of the flight control system will increase, and concurrently, maintenance costs will decrease.

B. Flight Control System Components

The S-3's flight control system is composed of several types of simple mechanical components. Examples are linkages, control rods, control cables, pulleys, and airframe control bearings. Each one of these components exhibits wear and failure patterns that can be measured, making each suitable for RCM analysis. Of these various hardware components, three were considered for this thesis. The decision to limit consideration to three components was based on RCM initiatives that are currently being addressed by the S-3 ISST. These three components are control cables, pulleys, and bearings. This analysis focuses on airframe control bearings, as an in-depth study has been completed on the control cables and pulleys[6].

1. Component Identification

Bearings of various capacities are used throughout the various flight control systems of the aircraft, and are either of the "radial ball" or "roller" bearing variety. Airframe bearings are usually of the radial ball bearing type, and they are available in single row, double row, extra-wide, self-aligning, and rod end types. These bearings are designed to withstand heavy radial loads in oscillation or slow turning applications, and in the case of rod end bearings, can be used to link other components such as connecting a flight control surface to a control rod [Ref. 6: p 450]. The S-3's Illustrated Parts Breakdown manual, the NAVAIR 01-S3AAA-4-1, identifies the various flight control systems and locations of each bearing. The S-3's flight control system is identified by the work unit code prefix of '14'.

Failure data provided by the ISST, Table 1, is a summary of 3M data, and shows that a total of 300 bearings failed over a seven-year period from 1990 to 1997. Of the 20 different bearing part numbers that were provided by the ISST, ten were selected for RCM analysis due to their higher failure rates. One of the ten was a rod end bearing; the remainders were radial ball bearings. Only one of the ten bearings requires external lubrication. 281 of these failures are of the ten part numbers (shown in bold face in Table 1) of interest since they represent 94 percent of total bearing failures. Table 1 lists the totals for each of the ten bearings.

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[6] NADEP North Island Engineering Report 001-95.

Table 1: **Bearing Failure Data**

Malfunction Code	*20*	*70*	*105*	*170*	*190*	*710*	*127*	*410*
Part Number								
DAT62-78A4	**14**		**3**			**1**		
KMDB16-9	**36**							
KMDB28-8	**35**							
MS21230-5	**25**	**2**	**3**					
MS21230-6	**27**		**4**	**3**				
MS21230-7	**11**				**2**			
MS21232-6	**14**							
SPH5-10B1-501	2							
SM5-7E-24	4		2		1			
REP4M6-4FS428	**15**	**1**					**1**	
REP4H6-FS428		1						
SPH5-8A								
SM4-4N1-502		1						
SF4-4A-24		1			1			
SM3-4A-24	1	2						
SM4-6D-22	1							
SM4-6D-22								
KP16BS-FS428	**35**				**2**			**4**
MS28913-4A	**41**		**1**			**1**		
MS28913-6A		1		1				
TOTALS	**261**	**9**	**13**	**4**	**6**	**2**	**1**	**4**

Malfunction codes identify the specific failure mode of the component at time of removal, and are defined by the OPNAV 4790.2E instruction [Ref.7: pp. I-3, I-4]. The majority of failures were shown has having a malfunction code of 20, which indicated wear as the failure mode.

Appendix A is a summary of 3M data provided by the Naval Aviation Maintenance Office (NAMO). Also shown is the work unit code (WUC), malfunction code, elapsed maintenance time (EMT), and total maintenance time by part number and manufacturer. This summary covers six years of reported data from 1992 through 1997.

Table 2 shows the number of each control bearing used in the flight control system

Table 2: **Quantities of Bearings Used in the Flight Control System**

Part Number	Quantity
DAT62-78A4	1
KDDB16-9	6
KMDB28-8	4
MS21230-5	4
MS21230-6	2
MS21230-7	1
KP16BS-FS428	10
REP4M6-4FS428	23
MS21232-6	1
MS289134A	1

A review of NAMO's 3M shows that of the ten bearings identified, only 142 failures were reported. This discrepancy was discussed with ISST team members, and it was noted that depot data is considered to be business sensitive and not merged with organizational and intermediate level data [Ref 8]. ISST failure data will be used for reliability calculations in favor of 3M data since the ISST has a larger repository of bearing data, as they are the CFA for the aircraft. 3M data will be used to determine organizational level man-hour usage and material cost.

2. Mean Time Between Failure Data

MTBF was calculated for each bearing using the following equation from Blanchard [Ref. 1: p. 29]:

$$MTBF = \# \text{ of reported failures} / \text{Total hours of operation}$$

As can be seen from Appendix A, each bearing can be used in several different areas of the flight control systems.[7] 79 different WUCs were identified in the 3M data. For this RCM analysis, failure data is segregated by part number in order to obtain a baseline MTBF by individual part number. Also, as bearings were obtained from more than one source calculated values of MTBF data were not individually determined by manufacturer, the assumption being that material and technological differences in bearing manufacture between manufacturers are relatively minor.

The fleet of S-3 aircraft flew a total of 362,383 hours over the seven-year period from 1990 to 1997. During this period, the total number of S-3 aircraft decreased from 164 to 134. Table 3 summarizes MTBF values for each bearing.

Table 3: **MTBF Data**

Part Number	Mean Time Between Failures (Hrs)
DAT62-78A4	20132
KMDB16-9	10066
KMDB28-8	10354
MS21230-5	12079
MS21230-6	10658
MS21230-7	27875
MS21232-6	25884
REP4M6-4FS428	21317
KP16BS-FS428	8839
MS28913-6A	8428

The number of failures that the ISST reported is based on replacement of the items at the organizational level, and does not reflect depot replacements. Currently, in complying with NADEP North Island Local Engineering Specifications (LES)[8], approximately 90% of all the bearings listed in Table 1 are replaced during SDLM, thus effectively lowering the calculated MTBF. [Ref 8] Therefore, the MTBF values shown are maximum values.

Of the ten part numbers, six have a MTBF of less than 13,000 hours. If the yearly average of fleet flight hours is 51,769 hrs, it is readily evident that at least one of each of these bearings will have to be replaced every year by organizational level maintenance personnel. For this reason, maintenance man-hour utilization discussed in the next section will focus on the organizational level.

3. Organizational Level Man-hour Cost Calculations

3M data was used to determine man-hour costs. Man-hour costs for Navy enlisted personnel of $22.33 per hour, were taken from NAVAIR's Default Data Guide (DDG) for Level of Repair Analysis [Ref 7: p. 4]. The DDG provides data that is set by Navy policy, such as manpower costs. Total man-hour costs were determined by multiplying the enlisted manpower rate by the total man-hours used for each maintenance action, for each bearing part number. Man-hour costs over the six-year period of 3M data were $62,941. Total man-hours expended in corrective maintenance were 2819. Table 4 summarizes man-hour cost data for each of the bearings.

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[7] Work unit codes identify the specific system or subsystem that each component is used in. 14xxxxx series identify the system as a component of the flight control systems group.
[8] LES are local requirements/inspections performed on an aircraft by depot level personnel during SDLM periods.

Table 4: **Man-Hour Cost**

Part Number	Elapsed Maintenance Time	Total Man Hours Expended	Total Man Hour Cost
MS289134A	289.10	691.70	$15,445.66
MS21232-6	264.70	578.60	$12,920.14
REP4M6-4FS428	115.80	152.90	$ 3,141.26
KMDB28-8	35.20	49.70	$ 1,109.80
MS21230-5	174.89	298.23	$ 6,659.55
MS21230-6	95.30	165.05	$ 3,685.57
MS21230-7	76.60	154.50	$ 3,449.99
DAT62-78A4	133.40	382.20	$ 8,534.53
KMDB16-9	70.70	119.10	$ 2,659.50
KP16BS-FS428	50.20	226.70	$5,062.21
TOTALS		2,818.68	$62,941.20

4. Component Cost Data

Unit prices for each of the bearings were obtained from Commander, Naval Air Pacific, Technical Research Office, and is shown in Table 5. Replacement costs totaled $31,723.60, and were determined by multiplying unit cost by the number of reported failures (from ISST data).

Table 5: **Bearing Unit/Total Costs**

Part Number	# of replacements	Unit Cost	Total Costs
MS21230-7	13	$ 15.96	$ 207.48
MS289134A	43	$ 46.14	$ 1,984.02
REP4M6-4FS428	17	$ 46.74	$ 794.58
KMDB28-8	35	$209.40	$ 7,329.00
MS21230-5	30	$ 11.61	$ 348.30
MS21230-6	34	$ 11.24	$ 382.16
MS21232-6	14	$ 10.34	$ 114.76
DAT62-78A4	18	$654.54	$11,781.72
KMDB16-9	36	$191.84	$ 6,906.24
KP16BS-FS428	41	$ 45.74	$ 1,875.34
TOTALS	281		$31,723.60

Seven of the ten bearings have unit costs that are less than $50.00 each, and their replacement costs totaled $5,707. These seven bearings represented only 18 percent of the total replacement costs. The three bearings with unit prices in excess of $100.00 represented 82 percent of total replacement costs.

C. Military Specifications and Aircraft Control Bearings

Aircraft control bearings used in Naval aircraft are manufactured accordance with U.S. Government standards dexcribed in the applicabel military specifications (MILSPEC). MIL-B-7949E, dated 9 April 1981 is the current specification. MIL-B-6039E is applicable to rod end bearings (REP4M6-4FS428 is the only rod end bearing is this study). Both of these MILSPEC prescribe material caharacteristics, axial and radial load ratings that have to be achieved. Qualification of radial dynamic loading is accomplished by applying a specified radial load in a test fixture and oscillating the bearing through an arc of 90 degrees and bac to the starting position for 15,000 cycles. The bearings are then inspected for looseness and excessive roughness. MIL-B-6039 adds the additional requirement that the rod end be exposed to a dusty environment as part of the test. Neither MILSPEC requires simulation of the aircraft's operating environment, and while bearing performance can satisfy MILSPEC, real world results may not be satisfactory.

In his 1994 memorandum "Specifications and Standards - A New Way of Doing Business", former Secretary of Defense William Perry state that the Department of Defense must increase access to commercial state of the art technology.[9] Bearing

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[9] SECDEF Policy Memo on MILSPEC & MILSTD Reforms, 22 June 94.

manufacturers are still using MILSPEC to qualify airframe control bearings that they provide to DOD, primarily due to safety concers. Continued dependence on MILSPEC provides no incentive for bearing manufacturers to provide more advanced bearings even though the technology is currently available to do so [Ref 11].

D. Summary

In a seven-year period from 1991 to 1997, twenty different airframe bearings in the S-3's flight control system had 300 documented failures. Of these twenty, ten bearings exhibited ten or more failures, and these ten were selected for RCM analysis. On average, this equates to seven or less failures per year for each part number for the entire fleet of 132 S-3 aircraft. The remaining ten bearings had three or less documented failures, and had MTBF rates in excess of 50,000 hours.

Each of the ten bearings conform to military specifications developed in the 1980s. Manufactures still use MILSPEC to supply bearings to DOD, even thought the majority of them are manufacturing bearings that significantly exceed the MILSPEC oscillation standard.

For the seven-year period, organizational level maintenance man-hours used to replace the failed bearings totaled $63,000.00 Bearing replacement costs were $31,723.00 Total combined costs were $94,723.00.

V. THE IRCMS ANALYSIS OF SELECTED BEARINGS

A. Introduction

The IRCMS is the Naval Air Systems Command's software program for performing and documenting the RCM and FMECA. Commercial software can also be used for RCM analysis, however, approval is required from AIR-3.2B.[10] The software used in this analysis was downloaded via the Internet, from the Naval Aviation Maintenance Office home page.

The program follows the logic contained in the NAVAIR 00-25-403 RCM management manual. Based upon input to the decision logic used in the program, IRCMS will recommend either: (1) no changes required, (2) a change in PM requirements, or (3) component redesign. The analysis can be performed on stand-alone IBM compatible personal computers. The current version of the software is 5.3.1.

B. The RCM Analysis Process

NAVAIR's RCM process is summarized by the following steps, and is shown in Figure 1.

1) Functional Failure Analysis: defines equipment functions and functional failures.
2) Significant Item (SI) Selection: establishes which components and systems will be analyzed, and establishes the component/function as either structurally of functionally significant.

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[10] See NAVAIR 00-25-403, page 1-1.

3) RCM Decision Logic: determines failure consequences, PM changes, and potential redesign requirements for significant items.

4) Age Exploration (AE) Analysis: determines data gathering tasks needed to support the RCM analysis.

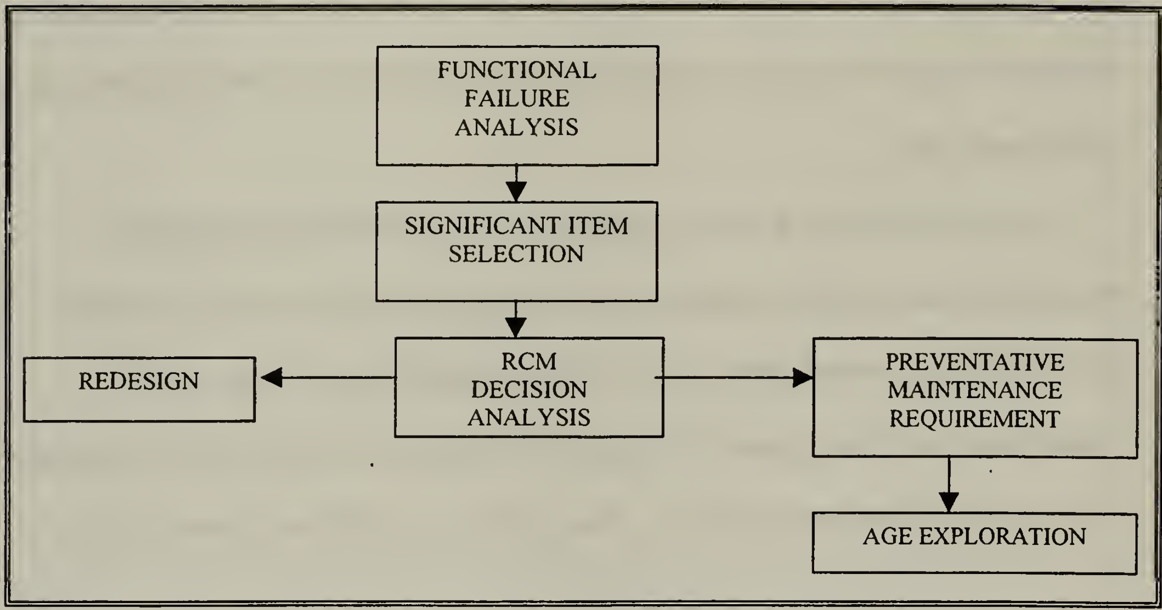


Figure 1: **RCM Analysis Process**

1. Functional Failure Analysis

Functional failure analysis is normally accomplished through a FMECA. The FMECA identifies the item, its functions, its functional failures, engineering failure modes, effects of failure on the item, and the failure detection method. Although the IRCMS can perform the FMECA [Ref. 4: p. 3-1], its application is not necessary for this study as all relevant information has been documented in the 3M database. The functions of the bearings being studied have been discussed in Chapter IV. Failures are assumed to be detected visually, and can be classified as jammed/frozen, or exhibiting corrosion. Bearings that are dislodged from their housings are also classified as having failed. And as stated in Chapter III, flight control component failure is considered to be a safety issue, therefor any failure is considered critical.

2. Significant Item Selection

Significant items (SI) are divided into 3 groups: structurally, functionally, and non-significant. The IRCMS determines an item's significance based on the analyst's answer to the following four questions [Ref. 4: p. 3-6]:

1) Does the function of the structural element carry major ground or aerodynamic loads?
2) Does the loss of the function cause an adverse affect on operating safety or mission abort?
3) Is the actual or predicted failure rate of the item or resources high?
4) Does the item have an existing PM requirement?

Structurally Significant Items (SSI) are identified to analyze components whose failures, if undetected, would have and adverse effect on safety. Components such as bearings used in flight control systems can be classified as either SSI or FSI, as they are subjected to aerodynamic loads. However, SSIs, which have non-structural functions such as rod, ends, hinges, and several of the bearings in this study, should be analyzed as both FSI and SSI [Ref.4: p. 3-4]. The program's FSI/SSI logic is shown by Figure 2. The

IRCMS software also allows for default answers to each of the four questions. The consequences of using default answers are shown in Figure 3

Each of the 10 bearings in this study was determined to be functionally significant through application of the FSI/SSI logic. SSI classification is suited to components that exhibit crack propagation, or are exposed to accidental damage. In answering question one, a decision has to made regarding the bearing's function in the system or subsystem, as bearings can be either a structural or functional component and SSI analysis is somewhat different from FSI analysis.

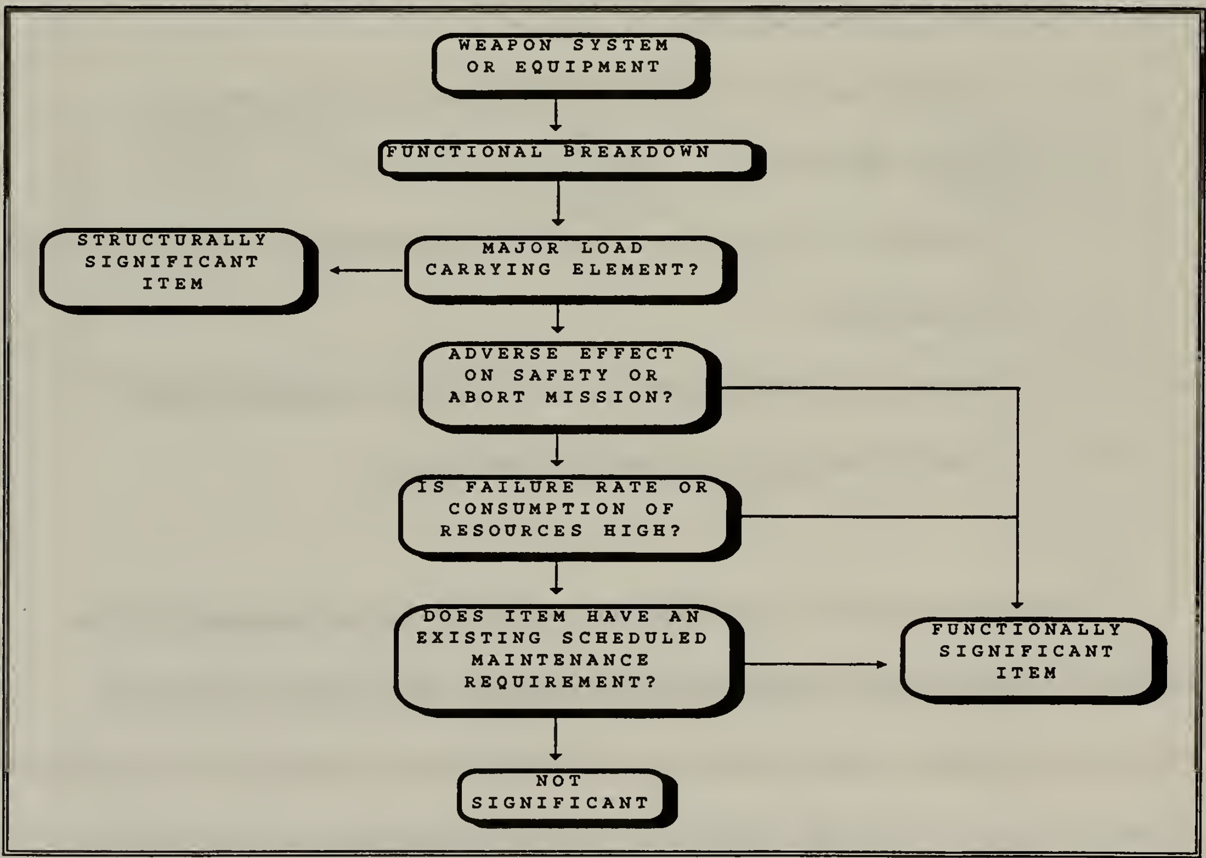


Figure 2: **FSI / SSI Decision Diagram**

3. RCM Decision Logic Applied to FSIs

After an item is determined to be functionally significant through the FSI/SSI selection logic, appropriate PM tasks are evaluated for applicability and effectiveness [Ref 4: p. 3-8]. This process is shown in Figure 3. "Applicability" determines if the task is appropriate for preventing the failure mode, and "effectiveness" determines if the task can be performed at some interval that will either reduce the probability of failure to an acceptable level.

Answers to the following three questions in the decision logic determine consequences of failure, and whether a PM task is applicable or redesign of the component warranted. The three questions that are answered:

1) Is the functional failure evident to the crew or operator while performing normal duties?
2) Does the engineering failure mode cause a function loss or secondary damage that could have an adverse effect on operating safety?
3) If the failure is hidden, does it have an adverse effect on operation safety?

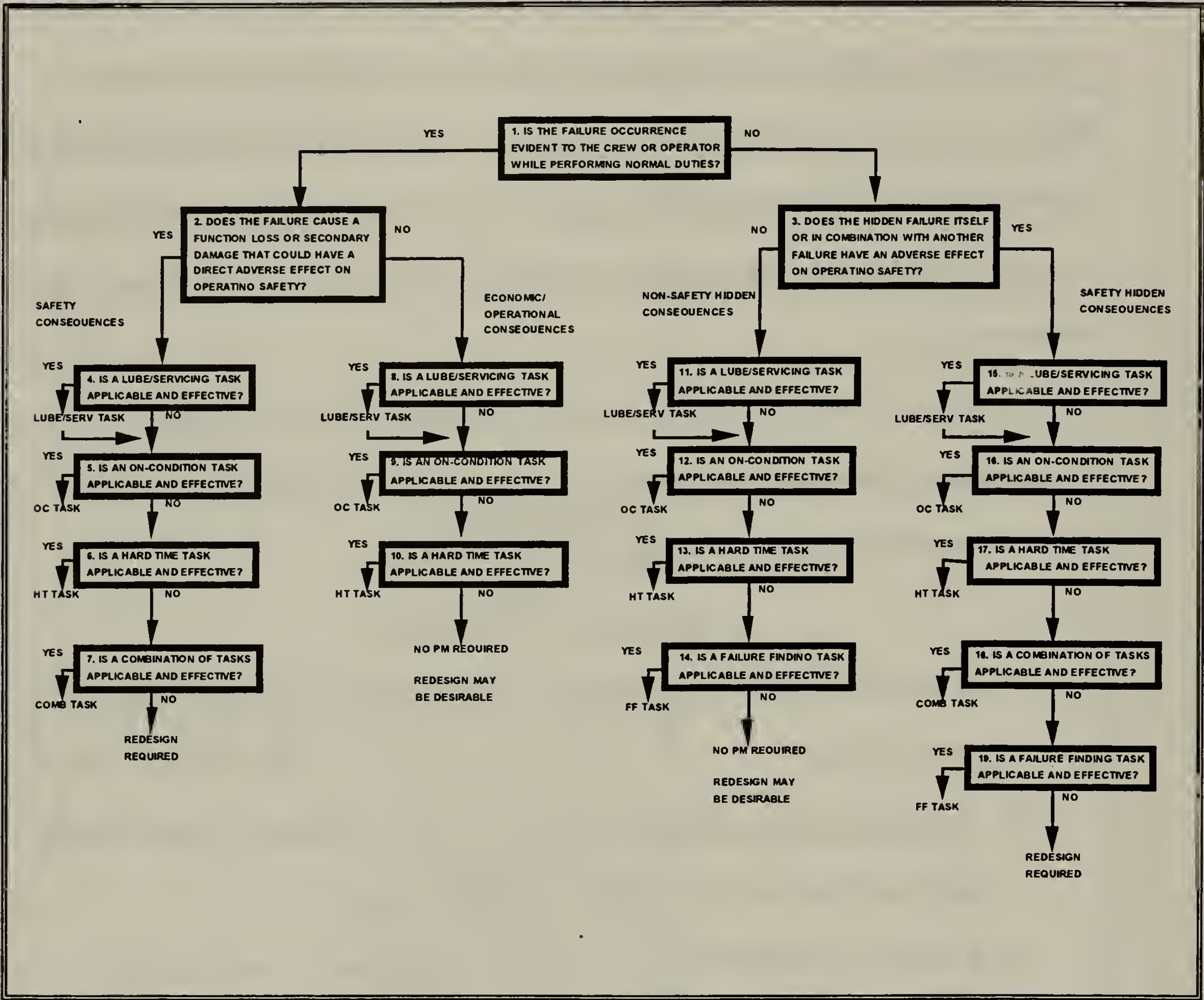


Figure 3: **RCM Decision Diagram for FSIs**

In answering question 1, a functional failure is evident only if it can be detected by the crew or maintenance technician performing normal duties, and the indication must be obvious to the crew or maintenance technician. Bearing failures may or may not be evident to the crew or maintenance technician, and there is no indication system in the aircraft to warn the crew of possible failure. Some bearing failures will be evident through visual inspection (non-hidden failures) performed during operational checks. However, other bearings are located in areas not accessible visually during periods of normal operation or periodic maintenance. Functional failure of bearings in this category will not be evident (hidden), and some disassembly of components will be necessary to determine causes of failure.

The answer to question 1 determines whether question 2 or 3 is answered next. In either case, both questions have two failure consequences, and each consequence has a set of tasks that require evaluation for effectiveness and applicability. For question 2 the failure consequences are either safety, or economic/operational. For question 3, the consequences are either non-safety hidden, or safety hidden. Figure 4 summarizes the effect of failure consequences on effectiveness and applicability criteria [Ref. 4: p3-11].

In this study, while the answer to question 1 could either be "yes" or "no" for each of the ten bearings being analyzed, the answer to both questions 2 and 3 should be "yes". This is done for two reasons. First, as mentioned in Chapter IV, 300 failures were reported in ISST data, and the ten bearings selected for RCM analysis are found in 79 different subsystems of the S-3's flight control system. Each bearing would have to be analyzed using the logic shown in Figure 2. Although there are four failure consequences (two for each of the paths that can be followed), the first three tasks are identical. Secondly, since bearings used in the flight control system can be considered as critical to maintaining system operability and safety, the answer to either question 2, or 3 would have to be "yes" also. This approach is justified by comparing the two paths that can be followed. Both have safety consequences and have similar task possibilities, the exception being the additional Failure Finding task option in the Safety Hidden path.

<table>
<tr><td rowspan="4"></td><td colspan="4">FAILURE CONSEQUENCES</td></tr>
<tr><td>SAFETY</td><td>OPERATIONAL /ECONOMICS</td><td>NON-SAFETY HIDDEN FAILURE</td><td>SAFETY HIDDEN FAILURE</td></tr>
<tr><td colspan="4">EFFECTIVENESS CRITERIA FOR ALL TASKS</td></tr>
<tr><td>Must reduce risk of failure to an acceptable level</td><td colspan="2">Must be cost effective; Cost of preventive maintenance must be less than cost of operational loss and/or cost of repair</td><td>Must reduce risk of multiple failures to an acceptable level</td></tr>
<tr><td>TASK</td><td colspan="4">APPLICABILITY CRITERIA</td></tr>
<tr><td>SERVICING/ LUBRICATION</td><td colspan="4">The replenishment of the consumable or lubricant must be due to normal operation and called for by the design</td></tr>
<tr><td>ON-CONDITION (OC)</td><td colspan="4">1. Must be possible to detect reduced failure resistance
2. Must have a definable, detectable potential failure condition
3. Must have a consistent age from potential failure to functional failure</td></tr>
<tr><td>HARD TIME (HT)</td><td>1. Must have minimum age below which no failures will occur

2. REWORK ONLY) Must be possible to restore to an acceptable level of failure resistance</td><td colspan="2">1. Must have age where conditional probability of failure shows a rapid increase

2. A large percentage of items must survive to this age

3. (REWORK ONLY) Must be possible to restore to an acceptable level of failure resistance</td><td>1. Must have minimum age below which no failures will occur

2. (REWORK ONLY) Must be possible to restore to an acceptable level of failure resistance</td></tr>
<tr><td>FAILURE FINDING</td><td colspan="2"></td><td colspan="2">No other task is applicable and effective</td></tr>
</table>

Figure 4: **Applicability and Effectiveness Criteria Summary**

The four tasks that are shown in Figure 3 are summarized as follows:

1. Service/Lubrication task, which is applicable if the design of the item requires periodic application of lubricant to avoid the failure mode.
2. On Condition task, which is a scheduled inspection for a potential failure condition.
3. Hard Time task, which is a scheduled removal of an item.
5. Failure Finding task, which is used only if on condition or hard time tasks are not effective for hidden failure modes.

Although not shown in Figure 3, Age Exploration tasks can also be accomplished. AE tasks are developed to collect data to refine default decisions or data included in the initial RCM analysis. AE tasks may be actual inspections or tests, or simply reviews of usage or failure data [Ref. 4: p. 3-21].

4. IRCMS Recommendations

The IRCMS manual describes the procedures of data entry into the software. The process is relatively straightforward, but familiarity with the software is recommended in order to minimize the time consumed in performing the analysis.

IRCMS provides the analyst fourteen different reports. These reports summarize the SI total, Failure Modes and Effects, PM Requirements, Failure Consequences for each of the tasks shown in Figure 3, and Failure Modes / Resulting PM [Ref.10: pp. 18-20].

Using the initial assumptions stated in Chapter III, each of the ten bearings was inputted into the program. The IRCMS recommended that each bearing should be redesigned. No On-Condition, Hard Time, or Failure Finding tasks were suggested for any of these bearings. Figure 5 shows an example of a "Failure Modes/Resulting PM" report for bearing DAT62-78A4.

```
MASTER ANALYSIS REPORT
PRELIMINARY REPORT INFORMATION

FAILURE MODE / RESULTING PM REQUIREMENT REPORT FOR BEARINGS

PRELIMINARY REPORT INFORMATION

LCN: DAT62-78A4        FMI:01A01          SIGNIFICANT ITEM: FUNCTIONAL

ENGINEERING FAILURE MODE: WEAR

SEVERITY CODE:         MTBF:       20132                Pacc:0.0

FAILURE CONSEQUENCES: SH

SAFETY?: Y

JUSTIFICATION:
FLIGHT CONTROL SYSTEM SAFETY IS COMPROMISED

EVIDENT?: N

JUSTIFICATION:

IS NOT READILY EVIDENT TO CREW

ANALYST: LCDR KING                              DATE: 11/15/97

FUNCTION JUSTIFICATION:

        ROD END BEARING IS CRITICAL TO SYSTEM INTEGRITY

FAILURE JUSTIFICATION:

EFM JUSTIFICATION:

RCM RESULTS

REDESIGN REQUIRED?: Y
```

Figure 5: **IRCMS Failure Effects/PM Requirement Report**

C. Summary

NAVAIR's IRCMS program was used to analyze each of the ten bearings being studied. Based on the author's initial assumptions developed in Chapter III, the program recommended that each be redesigned. Redesign options of bearings will be discussed in Chapter VII.

VI. RELIABILITY MODELING OF BEARINGS

A. Introduction

As is the case with other mechanical components, bearings are prone to wear and failure. There are various causes for these failures, and according to one survey, 30% were traced to the vendor, 66% to the end user, and 4% to external causes [Ref. 11]. The problems attributed to the vender were incorrect material used for construction, design errors, and less than optimal workmanship. User induced failures were attributed to poor maintenance practices, wear, and failure of monitoring equipment. External problems consisted of contaminated lubricants or faulty lubricant supply systems.

As mentioned in Chapter IV, wear was the primary failure mechanism noted for the bearings being studied. However, this wear is primarily a result of normal operations for control bearings. The author proposes that improvements in bearing quality will improve wear characteristics. Through application of statistical analysis, the effect of increasing bearing MTBF on maintenance costs will be presented.

B. Mathematical Background

1. Failure Rate Curves

Mathematical analyses of many mechanical and electronic components have shown that failure characteristics follow definite patterns. A plot of failure rate verses time of a component like a bearing is shown in Figure 6. This curve is known as the "bathtub curve" due to its shape. In Figure 6, the initial failures for 0 to T_1 are caused by problems traced to the vendor. This period is called the *infant mortality* period. The

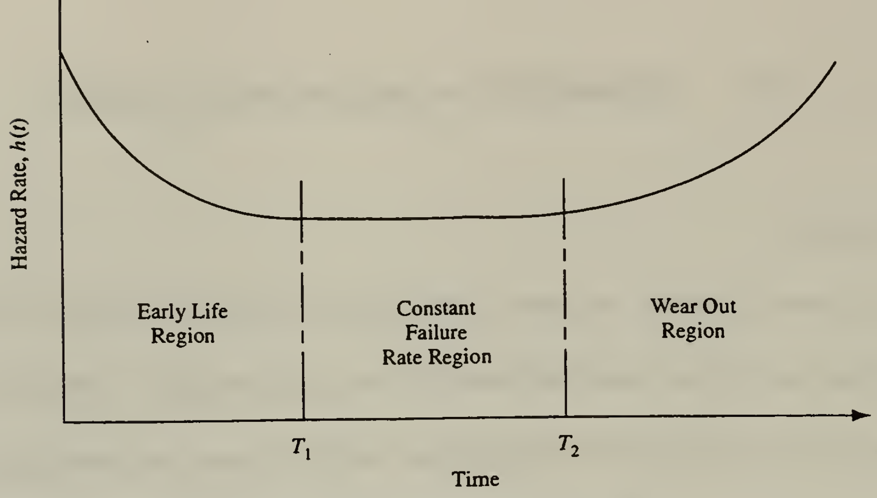


Figure 6: **Reliability Bathtub Curve**

period from T_1 to T_2 is called the *normal/operating* period, and failures in this period are caused by random overloads and chance failures, and attributed to the user. The normal period is also the period in which failure rates are constant and minimum. This is also the period where reliability is the highest, and the least number of failures occur. The last period, T_2 to T = infinity, is the wear out period. Failures in this period are due to excessive wear after the expected useful design life has been exceeded. The rate of failures increases rapidly in this period.

2. Reliability Functions

Reliability was defined in Chapter II in terms of probability. Through application of probabilistic theory, reliability of bearings can be calculated. The mathematical equations used in the mathematical model were adapted from Rao [Ref. 12].

The reliability R(t) of a bearing at some time *t* is defined as:

$$R(t) = e^{-\lambda t}$$

This equation assumes that the failure times follow an exponential distribution.

C. Spare Part Level Calculations

When the failure time of a component (like a bearing) follows an exponential distribution, the number of failures in a specified time follows a Poisson distribution [Ref. 12]. The probability of having *n* failures in time *t* is given by:

$$P(n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

where λ = 1/MTBF. The probability of having enough replacement parts if *r* spares are stocked at the beginning of the period is calculated by summing the individual probabilities over the range of 0 to *r* number of replacement parts.

When $\lambda\, t_o$ is sufficiently large (e.g. greater than 20) a simpler formula, using the central limit theorem, can be used to determine the number of spares needed in a resupply lead time, t_o,:

$$NS = \lambda\, t_o + Z_{1-\alpha}\,(\lambda\, t_o)^{1/2}$$

where $\lambda\, t_o$ is the mean of the number of failures in time t_o, and $(\lambda\, t_o)^{1/2}$ is the standard deviation. $Z_{1-\alpha}$ is the value of the standard normal variate corresponding to the confidence level α.

D. Mathematical Model of Historical Failure Data

Using a combination of reliability functions, historical failure data, and 3M data, a mathematical model was constructed to determine both bearing reliability and its associated maintenance costs. Poisson probabilities were calculated in order to determine quantities of replacement parts to support the individual part numbers for a 90 day period[11]. Cost data used in the model are the same as used in Chapter IV.

1. Man Hour and Component Costs

Table 6 is a summary, by part number, of MTBF, failure rate, % of total failures, # of expected maintenance actions per year, total bearing replacement cost per year, total maintenance cost per year, and the component cost for two SDLLM replacements. Total replacement costs per year using the current bearings averaged $12,782 for the seven year period. This total includes the cost of replacement at the depot. MTBF values, total component failure data, and unit costs are the same as presented in Chapter IV. The failure rate, which is the number of failures per unit of time is simply the inverse of the MTBF.

Table 6 : **Historical Failure Data**

Part Number	MTBF	Fail Rate	Exp #fails	Unit cost	Parts Costs/yr	Mnhr cost/yr	Total Replacement Cost/yr	SDLM Replacement cost
MS289134A	8,428	0.00012	6	$46.14	$276.84	$2,102.08	$2,378.92	$369.12
KP16BS-FS428	8,839	0.00011	6	$45.74	$274.44	$611.44	$885.88	$914.80
KMDB16-9	10,066	0.00010	5	$191.84	$959.20	$433.84	$1,393.04	$2,302.08
KMDB28-8	10,354	0.00010	5	$209.40	$1,047.00	$393.01	$1,440.01	$1,675.20
MS21230-6	10,658	0.00009	5	$11.24	$56.20	$818.48	$874.68	$44.96
MS21230-5	12,079	0.00008	5	$11.61	$58.05	$111.65	$169.70	$92.88
DAT62-78A4	20,132	0.00005	3	$654.54	$1,963.62	$1,117.06	$3,080.68	$1,309.08
REP4M6-4FS428	21,317	0.00005	3	$46.74	$140.22	$554.10	$694.32	$2,150.04
MS21232-6	25,884	0.00004	2	$10.34	$20.68	$844.39	$865.07	$20.68
MS21230-7	27,875	0.00004	2	$15.96	$31.92	$488.71	$520.63	$31.92
Totals			42		**$4,828.17**	**$7,474.75**	**$12,302.92**	**$8,910.76**

[11] LORA Data Guide specifies 90 days for CV units, therefor this value is used for maximum resupply lead time.

Blanchard [Ref. 1: p. 142] states that the expected number of maintenance actions per year is given by:

$$\frac{\textbf{Total operating hours per year}}{\textbf{MTBF}}$$

Replacement costs per year are determined by multiplying the expected number of maintenance actions per year, by the unit cost of the bearing. Man hour costs are determined by multiplying the expected number of failures per year by the average man hour by the utilization for each part number x man hour cost per hour. Total replacement cost per year is the sum of replacement cost and man-hour cost.

Component reliability over one year's operating time is given by:

$$R(t) = e^{-\lambda t}$$

Table 7 shows the results for each of the ten bearings. Individual bearing reliability ranges from a low of 72% to a high of 91%.

Table 7 : **Component Reliability**

PART NUMBER	RELIABILITY
MS289134A	0.72
KP16BS-FS428	0.73
KMDB16-9	0.76
KMDB28-8	0.77
MS21230-6	0.77
MS21230-5	0.80
DAT62-78A4	0.87
REP4M6-4FS428	0.88
MS21232-6	0.90
MS21230-7	0.91

2. Poisson Distributions

Poisson distribution calculations are shown in Appendix B. An operating time of 79, 460 hrs was used. This value was obtained by multiplying the average number of aircraft in the fleet by the average number of flight hours for each aircraft[12]. The probabilities for *n* number of failures per year are shown as well as the cumulative probabilities for *n* <= to *r* failures. Appendix C shows all ten distributions graphically.

3. Spare Part Levels

Based on Poisson distributions, a lead-time of 90 days, and a confidence level of 90% for part availability, individual quantities of spare parts for each part number were calculated. Required levels are shown in Table 8. From this it is seen that based on current failure rates, relatively small quantities of each bearing needs to be held in inventory for S-3 support.

Table 8 : **Spare Part Levels Required for a 90 Day Lead Time**

PART NUMBER	SPARES REQUIRED FOR 90 DAY LEAD TIME
MS289134A	2
KP16BS-FS428	2
KMDB16-9	2
KMDB28-8	2
MS21230-6	2
MS21230-5	2
DAT62-78A4	1
REP4M6-4FS428	1
MS21232-6	1
MS21230-7	1

[12] The average flight hours per aircraft were 548 hrs/yr. This value was obtained from NADEP North

4. Life Cycle Costs

Assuming that the S-3 will remain in the Navy's inventory for another 15 years (until the year 2013), remaining life cycle costs were determined using currently available bearings. The total life cycle cost of replacing these bearings will total $210,000 (not adjusted for inflation).

E. Improved Bearings and Mathematical Model Results

Through use of modern technology and processes to manufacture airframe control bearings, operating life can be extended without modification to the existing bearing functional envelope. Recent advances in bearing design and manufacturing technology provides a cost-effective ability to increase bearing life. The term "power density" is commonly used to describe this concept of applying technology enhancements to maximize performance [Ref. 13]. Various degrees of power density can be applied to enhance bearing life and durability. These enhanced bearings will provide a minimum of 1.5 times the life of a standard bearing, although gains of 4-5 times are not uncommon [Ref. 13].

Each of the ten bearings being studied were originally based on 1970s technology and military specifications (MILSPEC). By applying 1990s technology and the concept of power density to these bearings, individual component reliability can exceed current MILSPEC for control bearings. New bearings are currently available from various bearing manufacturers that are direct replacements, and incorporate several technologies that result in a bearing that is more durable and corrosion resistant than those now being used in the flight control system. Kamatics Corporation in Bloomfield, CT, which is a division of Kaman Bearings, provided recommendations for substitute control bearings for this study. Kamatics bearings utilize stainless steels in both the bearing races and the rolling elements [Ref. 15]. In doing so, the hardness ratings of the bearing are increased, and at the same time, corrosion resistance is also significantly improved. The improved corrosion resistance is especially important as bearing corrosion is more of a concern to manufacturers than is bearing wear [Ref. 11].

1. Model Output Using Improved Bearings

The model used for the improved bearings is the same as the historical failure data model. Poisson distributions and spare part levels were calculated similarly as well. In this model, higher estimates for MTBF, and unit costs of the new bearings are entered into the model, and the results are compared to the historical model. Based on the assumption that by using Kamatics Corporation improved bearings, MTBF for each bearing could be increased by a factor of three. Table 9 summarizes the new MTBFs, expected failure rates, unit costs, and total maintenance costs estimates using the new bearings. Unit cost figures are current market prices based on a minimum quantity order, and do not represent final costs that would be determined through normal federal acquisition procedures. Appendix D shows the Poisson distribution for the expected number of failures using improved bearings.

Table 9 : **Improved Bearing Failure/Cost Data**

Current Part Numbers	New Part Numbers	MTBF	Failure Rate	Exp Failures	Unit Cost	Mnhr Cost/yr	Parts Cost/yr	Total Replacement Costs/yr	SDLM Replacement Cost
DAT62-78A4	KSC230162RM	60,396	0.000017	2	$396.15	$744.93	$792.30	$1,537.23	$396.15
KMDB16-9	KSC181700V-2	30,198	0.000033	3	$142.25	$260.59	$426.75	$687.34	$853.50
KMDB28-8	KSC181700V-1	31,062	0.000032	3	$169.15	$235.80	$507.45	$743.25	$182.96
KP16BS-FS428	KRP16BSV	26,517	0.000038	3	$140.00	$305.47	$420.00	$725.47	$1,400.00
MS21230-5	KSC231005V	36,237	0.000028	2	$52.30	$372.02	$104.60	$476.62	$209.20
MS21230-6	KSC231006V	31,974	0.000031	3	$50.10	$491.04	$150.30	$641.34	$131.90
MS21230-7	KSC231307V	83,625	0.000012	1	$65.95	$244.29	$65.95	$310.24	$65.95
MS21232-6	KSC231206V	77,652	0.000013	1	$66.00	$422.26	$66.00	$488.26	$66.00
MS289134A	**TBA**	25,284	0.000040	3	$58.00	$1,051.07	$174.00	$1,225.07	$58.00
REP4M6-4FS428	MS21151-8C	63,951	0.000016	2	$113.60	$369.34	$227.20	$596.54	$2,612.80
TOTALS				23		$4,496.82	$2,934.55	$7,431.37	$6,353.50

As a result of increased MTFB, the spare part quantities required for S-3 support are reduced by 50 percent, and only one SDLM preventative maintenance change-out is necessary. Table 10 shows the effect of increasing MTBF on bearing reliability. New reliability figures range from 90% to 97% as compared to the historical reliability of 72% to 91%. The percent improvement of new bearings over the old bearings is also shown.

Table 10 : **Reliability Data for Enhanced Bearings**

PART NUMBER	NEW RELIABILITY	PERCENT IMPROVEMENT
KSC230162RM	0.96	9.83%
KSC181700V-2	0.91	20.13%
KSC181700V-1	0.92	18.87%
KRP16BSV	0.90	23.49%
KSC231005V	0.93	15.86%
KSC231006V	0.92	19.17%
KSC231307V	0.97	6.34%
KSC231206V	0.97	7.25%
TBA	0.90	24.58%
MS21151-8C	0.96	8.85%

Table 11 summarizes costs for the current bearings and the improved bearings. A reduction of 48% in control bearing maintenance costs can be achieved if the new bearings can actually achieve desired MTBF.

Table 11: **Comparison of Current and Improved Bearings**

Cost Component	Current Bearings	Improved Bearings
Mnhr Cost/yr	$7,474.75	$4,496.82
Part Cost/yr	$4,828.17	$2,482.47
Total Replacement Cost/yr	$12,302.92	$6,979.29
SDLM Replacement Cost	$8,910.76	$3,484.22
Total/yr	$33,516.60	$17,442.80

Models for both historical data and expected failure data are presented in appendix A and B respectively.

Although the annual dollar figures involved are not significant, the savings in maintenance man-hours are important, as fewer failures will occur as a result of increased mean time between failures. However, the increases in reliability and system safety that can be obtained by replacing the current bearings should be more of a determining factor in the decision whether to pursue the option of changing to the new bearings.

F. Summary

A mathematical model was developed to perform statistical analyze of historical failure data for the control bearings. In analyzing the bearings, the exponential failure distribution was used due to a lack of engineering data, which precluded the use of other distributions, such as the Weibull Distribution. Spare part levels were also determined using the Poisson Distribution. Based on a ninety day lead time and historical failure rates, no more than two of each part number has to be maintained in the supply inventory. Cost projections for bearing replacement were developed for the remaining life of the S-3 aircraft.

Analysis of advanced bearings was also performed in order to compare historical failure data with estimated failure data of advanced bearings. The advanced bearings incorporate modern manufacturing processes and materials that can extend current bearing life by a factor of four to five times. In the advanced bearing model, bearing life was extended by a factor of three, and new cost and reliability data was determined. With the new bearings installed, total maintenance costs could be reduced by 48 percent per year, and individual bearing reliability estimates increased by 6 to 24 percent.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. Introduction

NAVAIR's Reliability Centered Maintenance Analysis process was applied to the airframe control bearings used in the Navy's S-3 aircraft flight control system, in order to determine if improvements in bearing reliability and maintainability can be achieved. The IRCMS program was used to analyze each of the ten bearings being studied. Based on the initial assumptions developed in Chapter III, the program recommended that each bearing should be redesigned. Redesign, in the case of control bearings, requires use of modern materials and processes. Through use of bearings that incorporate these advances, expected failure rates can be reduced by 50 percent, and life cycle cost reductions of 48 percent. This chapter provides conclusions and recommendations regarding aircraft control bearings.

B. Conclusions

1. Ten aircraft control bearings used in the flight control system of the S-3 aircraft exhibit poor reliability.

During the last seven years, 300 S-3 aircraft control bearings were replaced fleet wide. Of the twenty bearing part numbers that were monitored, ten bearings had ten or more failures per year. The remaining ten had three or less failures per year. Bearing failure data is summarized in Table 1. Reliability values for the bearings is shown in Table 7.

2. **IRCMS analysis recommends that each of the ten bearings should be redesigned.**

NAVAIR's IRCMS program was used to analyze each bearing, and based on initial assumptions developed for this thesis, the program recommended that each should be redesigned. Each of the ten bearings was classified as being functionally significant through application of the FSI/SSI logic shown in Figure 2. Figure 3 shows the decision logic that was used to reach the redesign conclusion for FSIs.

3. **Aircraft control bearing reliability can be increased through application of advanced manufacturing processes, without increasing life cycle costs.**

Through use of modern technology and processes to manufacture airframe control bearings, operating life can be extended without modification to the existing bearing functional envelope. Recent advances in bearing design and manufacturing technology provides a cost-effective ability to increase bearing life. These enhanced bearings will provide a minimum of 1.5 times the life of a standard bearing, although gains of four to five times are not uncommon.

4. **Inventory levels of aircraft control bearings for S-3 support require only small annual quantity purchases.**

Based on a mathematical analysis of historical failure data, less than ten of each part number has to be maintained in the inventory on an annual basis. Large quantity purchases for S-3 support are not required, and if the improved bearings can achieve the anticipated increase in MTBF, inventory levels can be decreased by almost 50 percent.

5. MILSPECs do not provide manufacturers with an incentive to provide DoD with more advanced bearings.

MILSPECs are still being used by manufacturers to supply bearings to DOD. MIL-B-7949E, dated 9 April 1981, is the current specification. All the manufacturers contacted for this study have the capability to manufacture bearings that far exceed MILSPEC. MILSPEC testing does not accurately simulate an aircraft's operating environment and the results of such testing may result in a false indication of reliability.

C. Recommendations

1. Develop an Engineering Change Proposal requiring use of improved bearings in the flight control system to replace the ten bearings analyzed in this study.

NADEP North Island's ISST should begin a formal analysis and testing program using improved bearings. There are several manufacturers who can provide NADEP with bearings that can be tested.

2. Eliminate MILSPECs for control bearings, and use performance specifications for bearing acquisition.

DOD should eliminate MILSPECs for control bearings and instead use performance specifications as part of the acquisition process. This would result in DOD obtaining bearings that will meet an actual operating time requirement instead of exceeding an arbitrary number of oscillations in a test fixture.

APPENDIX A

PART NUMBER/WUC/MAL CODE/MAN-HOUR DATA

Data Source: Naval Aviation Logistics Data Analysis (NALDA)
Period Covered: January 1991 to June 1997

Legend:

P/N = Part Number
MANUF = Manufacturer's code
WUC = Work Unit Code
MAL CODE = Malfunction Code
EMT = Elapsed Maintenance Time
TOT MNHRS = Total Man Hours
AVG EMT = Average Elapsed Maintenance Time (in hours)

PART NUMBER	MANUF	WUC	MAL CODE	EMT	TOT MNHRS	TOT MNHR COST
MS21230-7	36659	1432010	105	4.80	4.80	$107.18
	36659	1472200	190	33.00	90.00	$2,009.70
AVG EMT	36659	1472210	20	1.00	1.00	$22.33
10.94	96906	1472210	20	12.50	19.90	$444.37
	96906	1472210	105	10.70	20.90	$466.70
	96906	1472300	20	3.30	6.60	$147.38
	36659	1432M00	20	11.30	11.30	$252.33
Totals				76.60	154.50	$3,449.99

REP4M6-4FS428	21335	1481800	615	1.50	1.50	$33.50
	21335	1481800	710	3.30	3.30	$73.69
AVG EMT	21335	1481800	020	3.10	3.10	$69.22
8.27	21335	1481800	020	3.00	3.00	$66.99
	21335	1481800	020	8.00	12.05	$269.08
	21335	1481800	020	11.50	15.05	$336.07
	21335	1481800	020	8.50	8.50	$189.81
	36659	1481800	020	4.30	4.30	$96.02
	36659	1481800	020	1.50	3.00	$66.99
	36659	1481800	020	2.50	3.50	$78.16
	36659	1482180	410	8.60	16.60	$370.68
	21335	13A1600	020	7.00	14.00	$312.62
	36659	13A6840	020	50.00	62.00	$1,384.46
	36659	13A6H40	030	3.00	3.00	$66.99
Totals				115.80	152.90	$3,414.26

KMDB28-8	97613	1181000	020	5.00	9.00	$200.97
	97613	1182000	020	4.00	4.00	$89.32
AVG EMT	97613	1191900	020	4.00	7.50	$167.48
3.52	97613	1431000	020	5.50	6.50	$145.15
	97613	1432300	020	1.80	1.80	$40.19
	97613	1432300	020	1.30	1.30	$29.03
	97613	1432300	020	4.00	7.50	$167.48
	97613	1432300	020	1.00	1.00	$22.33
	97613	1432600	020	4.00	6.50	$145.15
	36659	1432F30	020	4.60	4.60	$102.72
Totals				35.20	49.70	$1,109.80

MS21230-5	96906	1115000	814	23.20	46.90	$1,047.28
	96906	1181000	020	3.50	4.50	$100.49
AVG EMT	96906	1182200	020	12.08	62.25	$1,390.04
8.33	35368	1432540	070	0.50	1.00	$22.33
	96906	1432900	020	7.90	15.80	$352.81
	96906	1472210	020	4.17	6.43	$143.66
	96906	13A1900	020	11.10	14.10	$314.85
	36659	1431C80	020	3.10	3.10	$69.22
	96906	1432B00	020	6.00	9.00	$200.97
	96906	1432C00	020	12.25	12.25	$273.54
	36659	1432D10	020	4.10	4.10	$91.55
	36659	1432E00	105	20.50	20.50	$457.77
	96906	1432E00	105	1.80	1.80	$40.19
	96906	1432E00	846	39.70	52.30	$1,167.86
	96906	1432E00	020	1.00	1.50	$33.50
	96906	1432E10	105	5.00	9.00	$200.97
	96906	1432E10	105	4.80	9.30	$207.67
	36659	1432F10	020	2.50	5.00	$111.65
	36659	1432F40	020	4.10	8.20	$183.11
	36659	1432F40	020	3.60	7.20	$160.78
	96906	1481E10	020	4.00	4.00	$89.32
Totals				174.89	298.23	$6,659.55

MS21230-6	96906	1182200	020	6.10	12.50	$279.13
	36659	1472200	170	16.50	45.00	$1,004.85
AVG EMT	96906	1472210	020	6.25	9.95	$222.18
7.33	96906	1472300	020	1.65	3.30	$73.69
	96906	13A2Q20	020	18.00	22.50	$502.43
	96906	1432B00	020	6.00	9.00	$200.97
	96906	1432B00	020	2.50	2.50	$55.83
	96906	1432B00	020	7.50	15.00	$334.95
	96906	1432C00	020	12.25	12.25	$273.54
	36659	1432D00	020	4.70	11.70	$261.26
	96906	1432D00	020	3.80	5.80	$129.51
	36659	1432D10	105	6.00	11.50	$256.80
	36659	1432D10	020	4.05	4.05	$90.44
Totals				95.30	165.05	$3,685.57

MS21232-6	36659	1412590	020	15.10	15.10	$337.18
	96906	1412590	020	18.00	207.00	$4,622.31
AVG EMT	96906	1412590	020	7.40	12.60	$281.36
18.91	96906	1412590	020	10.40	15.70	$350.58
	96906	1412590	020	19.00	19.00	$424.27
	96906	1412590	020	19.40	31.20	$696.70
	96906	1412590	020	23.50	32.50	$725.73
	96906	1421100	020	12.70	16.30	$363.98
	36659	1412B10	020	10.30	13.30	$296.99
	96906	14211D0	020	21.50	42.50	$949.03
	96906	14211D0	020	53.20	77.90	$1,739.51
	96906	14211D0	020	27.40	45.70	$1,020.48
	96906	14211D0	020	13.30	26.40	$589.51
	96906	14211D0	020	13.50	23.40	$522.52
Totals				264.70	578.60	$12,920.14

DAT62-78A4	36659	1412200	020	78.00	270.00	$6,029.10
	77896	1412200	105	5.00	7.00	$156.31
AVG EMT	36659	1412300	020	1.30	2.60	$58.06
16.68	77896	1412500	020	9.30	22.60	$504.66
	77896	1412500	020	14.00	28.00	$625.24
	36659	1412510	020	7.70	14.60	$326.02
	77896	1412530	020	15.90	35.00	$781.55
	77896	1412570	135	2.20	2.40	$53.59
Totals				133.40	382.20	$8,534.53

KMDB16-9	97613	1181000	020	5.00	10.00	$223.30
	97613	1181000	020	5.00	9.00	$200.97
AVG EMT	97613	1432000	020	3.70	3.70	$82.62
3.89	97613	1432300	070	3.70	4.90	$109.42
	36659	1432600	020	3.70	16.80	$375.14
	97613	1481000	020	3.70	6.30	$140.68
	36659	1481630	020	3.70	3.00	$66.99
	36659	1481630	020	3.70	5.30	$118.35
	97613	1481630	135	3.70	15.00	$334.95
	97613	1481630	020	3.70	4.50	$100.49
	97613	1481630	020	3.70	5.30	$118.35
	36659	1484900	020	3.70	17.00	$379.61
	36659	1431C30	020	3.70	15.00	$334.95
	97613	1431C30	020	3.70	3.30	$73.69
Totals				54.40	119.10	$2,659.50

KP16BS-FS428	21335	1431300	020	1.50	3.00	$66.99
	21335	1431300	020	7.30	14.30	$319.32
AVG EMT	36659	1431400	020	0.90	0.90	$20.10
4.56	21335	1432300	020	10.10	11.10	$247.86
	21335	1432600	020	6.80	6.80	$151.84
	21335	030ASP0	020	2.80	2.80	$62.52
	21335	1113A30	020	2.25	3.75	$83.74
	21335	1113A30	020	2.75	2.75	$61.41
	21335	1113A30	020	5.30	10.30	$230.00
	21335	1113A30	710	10.00	170.00	$3,796.10
	21335	466D4E0	020	0.50	1.00	$22.33
Totals				50.20	226.70	$5,062.21

MS289134A	36659	1412300	020	84.00	264.00	$5,895.12
	36659	1412400	105	22.00	49.00	$1,094.17
AVG EMT	36659	1412500	020	5.50	6.90	$154.08
15.69	96906	1412500	020	22.50	50.50	$1,127.67
	96906	1412500	020	20.50	47.00	$1,049.51
	96906	1412500	020	28.50	65.00	$1,451.45
	36659	1412510	710	8.00	24.00	$535.92
	36659	1412510	020	28.50	50.60	$1,129.90
	36659	1412510	020	6.50	6.50	$145.15
	36659	1412510	020	9.80	18.80	$419.80
	36659	1412510	020	9.00	21.00	$468.93
	36659	1412510	020	7.90	11.90	$265.73
	96906	1412510	020	9.00	18.00	$401.94
	36659	1412570	020	8.60	16.60	$370.68
	96906	1421140	190	1.70	1.70	$37.96
	96906	1421160	020	1.90	1.90	$42.43
	96906	14121110	020	4.00	4.00	$89.32
	96906	1412B10	020	6.10	12.20	$272.43
	96906	1412B10	020	14.10	22.10	$493.49
Totals				298.10	691.70	$15,445.66

APPENDIX B

POISSON PROBABILITIES FOR HISTORICAL DATA

Legend:

P(n) = Probability of "n" number of failures
P(N<,= r) = Probability of "n" less than or equal to "r" number of failures

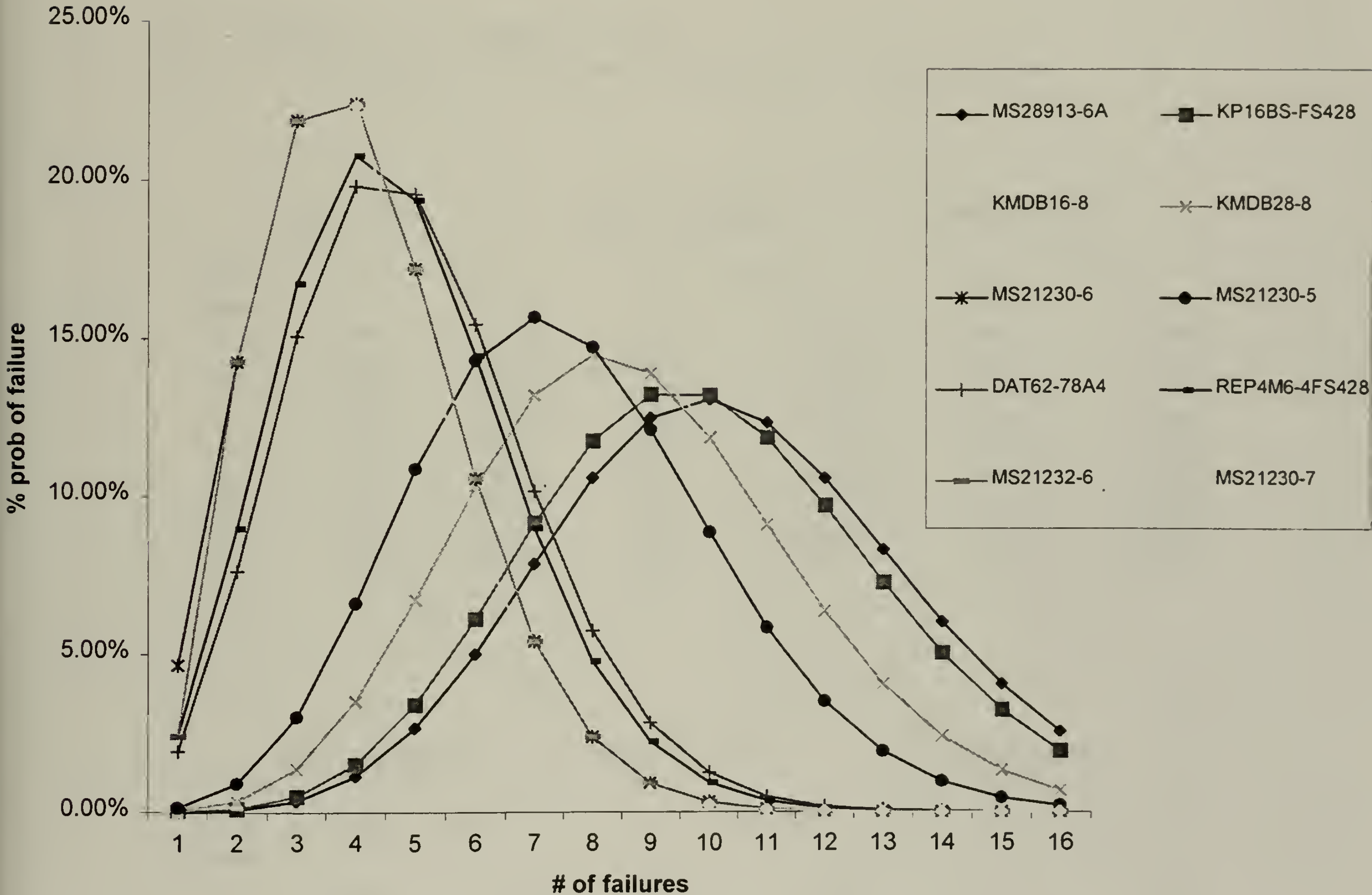
	MS289134A		KP16BS-FS428		REP4M6-4FS428	
n # of failures	P(n)	P(n<,= r)	P(n)	P(n<,= r)	P(n)	P(n<,= r)
0	0.01%	0.01%	0.01%	0.01%	2.41%	0.01%
1	0.08%	0.08%	0.11%	0.12%	8.97%	11.37%
2	0.36%	0.44%	0.50%	0.63%	16.71%	28.08%
3	1.12%	1.56%	1.51%	2.14%	20.76%	48.84%
4	2.65%	4.21%	3.39%	5.53%	19.35%	68.19%
5	4.99%	9.21%	6.10%	11.63%	14.42%	82.61%
6	7.85%	17.05%	9.14%	20.77%	8.96%	91.57%
7	10.57%	27.62%	11.74%	32.51%	4.77%	96.35%
8	12.45%	40.07%	13.19%	45.70%	2.22%	98.57%
9	13.05%	53.12%	13.18%	58.88%	0.92%	99.49%
10	12.30%	65.42%	11.84%	70.72%	0.34%	99.83%
11	10.54%	75.96%	9.68%	80.40%	0.12%	99.95%
12	8.28%	84.24%	7.25%	87.65%	0.04%	99.99%
13	6.01%	90.25%	5.01%	92.67%	0.01%	100.00%
14	4.05%	94.30%	3.22%	95.89%	0.00%	100.00%
15	2.54%	96.84%	1.93%	97.82%	0.00%	100.00%
16	1.50%	98.34%	1.08%	98.90%	0.00%	100.00%
17	0.83%	99.17%	0.57%	99.47%	0.00%	100.00%

n # of failures	KMDB16-9 P(n)	KMDB16-9 P(n<,= r)	KMDB28-8 P(n)	KMDB28-8 P(n<,= r)	MS21230-6 P(n)	MS21230-6 P(n<,= r)
0	0.04%	0.01%	0.05%	0.05%	4.64%	0.06%
1	0.29%	0.33%	0.36%	0.40%	14.25%	18.90%
2	1.16%	1.49%	1.37%	1.77%	21.88%	40.77%
3	3.06%	4.55%	3.50%	5.27%	22.39%	63.16%
4	6.04%	10.59%	6.71%	11.99%	17.18%	80.34%
5	9.53%	20.11%	10.31%	22.29%	10.55%	90.89%
6	12.54%	32.65%	13.18%	35.47%	5.40%	96.28%
7	14.14%	46.79%	14.45%	49.93%	2.37%	98.65%
8	13.95%	60.74%	13.86%	63.79%	0.91%	99.56%
9	12.23%	72.97%	11.82%	75.61%	0.31%	99.87%
10	9.66%	82.63%	9.07%	84.68%	0.10%	99.96%
11	6.93%	89.56%	6.33%	91.01%	0.03%	99.99%
12	4.56%	94.12%	4.05%	95.06%	0.01%	100.00%
13	2.77%	96.89%	2.39%	97.45%	0.00%	100.00%
14	1.56%	98.45%	1.31%	98.76%	0.00%	100.00%
15	0.82%	99.27%	0.67%	99.43%	0.00%	100.00%
16	0.41%	99.67%	0.32%	99.75%	0.00%	100.00%
17	0.19%	99.86%	0.15%	99.90%	0.00%	100.00%

n # of failures	MS21230-5 P(n)	MS21230-5 P(n<,= r)	MS21230-7 P(n)	MS21230-7 P(n<,= r)	MS21232-6 P(n)	MS21232-6 P(n<,= r)	DAT62-78A4 P(n)	DAT62-78A4 P(n<,= r)
0	0.14%	0.14%	5.78%	5.78%	2.41%	0.01%	1.93%	1.93%
1	0.91%	1.05%	16.48%	22.26%	14.25%	16.66%	7.62%	9.55%
2	3.01%	4.06%	23.49%	45.75%	21.88%	38.53%	15.04%	24.60%
3	6.60%	10.66%	22.32%	68.07%	22.39%	60.92%	19.79%	44.39%
4	10.85%	21.50%	15.90%	83.97%	17.18%	78.10%	19.53%	63.92%
5	14.27%	35.78%	9.07%	93.04%	10.55%	88.65%	15.42%	79.34%
6	15.65%	51.42%	4.31%	97.35%	5.40%	94.05%	10.14%	89.48%
7	14.70%	66.13%	1.75%	99.10%	2.37%	96.41%	5.72%	95.20%
8	12.09%	78.22%	0.63%	99.73%	0.91%	97.32%	2.82%	98.02%
9	8.84%	87.06%	0.20%	99.92%	0.31%	97.63%	1.24%	99.25%
10	5.81%	92.87%	0.06%	99.98%	0.10%	97.73%	0.49%	99.74%
11	3.48%	96.35%	0.01%	100.00%	0.03%	97.75%	0.18%	99.92%
12	1.91%	98.25%	0.00%	100.00%	0.01%	97.76%	0.06%	99.98%
13	0.96%	99.22%	0.00%	100.00%	0.00%	97.76%	0.02%	99.99%
14	0.45%	99.67%	0.00%	100.00%	0.00%	97.76%	0.00%	100.00%
15	0.20%	99.87%	0.00%	100.00%	0.00%	97.76%	0.00%	100.00%
16	0.08%	99.95%	0.00%	100.00%	0.00%	97.76%	0.00%	100.00%
17	0.03%	99.98%	0.00%	100.00%	0.00%	97.76%		

APPENDIX C

GRAPHICAL REPRESENTATION OF HISTORICAL FAILURE DATA



APPENDIX D

EXPECTED POISSON PROBABILITIES
FOR IMPROVED BEARINGS

Legend:

P(n) = Probability of "n" number of failures
P(N<,= r) = Probability of "n" less than or equal to "r" number of failures

	MS289134A		KSC230162RM		MS21151-8C	
n # of failures	P(n)	P(n<,= r)	P(n)	P(n<,= r)	P(n)	P(n<,= r)
0	7.4%	7.4%	45.4%	45.4%	42.7%	42.7%
1	19.2%	26.5%	35.8%	81.3%	36.3%	79.1%
2	25.0%	51.6%	14.1%	95.4%	15.4%	94.5%
3	21.8%	73.4%	3.7%	99.1%	4.4%	98.9%
4	14.2%	87.6%	0.7%	99.9%	0.9%	99.8%
5	7.4%	95.0%	0.1%	100.0%	0.2%	100.0%
6	3.2%	98.2%	0.0%	100.0%	0.0%	100.0%
7	1.2%	99.5%	0.0%	100.0%	0.0%	100.0%
8	0.4%	99.8%	0.0%	100.0%	0.0%	100.0%

	KSC181700V-2		KSC231106V		KSC231206V	
n # of failures	P(n)	P(n<,= r)	P(n)	P(n<,= r)	P(n)	P(n<,= r)
0	11.9%	11.9%	16.2%	16.2%	7.4%	7.4%
1	25.4%	37.3%	29.5%	45.7%	19.2%	26.5%
2	27.0%	64.3%	26.8%	72.5%	25.0%	51.6%
3	19.1%	83.4%	16.3%	88.8%	21.8%	73.4%
4	10.1%	93.5%	7.4%	96.2%	14.2%	87.6%
5	4.3%	97.9%	2.7%	98.9%	7.4%	95.0%
6	1.5%	99.4%	0.8%	99.7%	3.2%	98.2%
7	0.5%	99.8%	0.2%	99.9%	1.2%	99.5%
8	0.1%	100.0%	0.0%	100.0%	0.4%	99.8%
9	0.0%	100.0%	0.0%	100.0%	0.1%	100.0%

	KSC231005V		KSC231307V	
n # of failures	P(n)	P(n<,= r)	P(n)	P(n<,= r)
0	16.2%	16.2%	45.4%	45.4%
1	29.5%	45.7%	35.8%	81.3%
2	26.8%	72.5%	14.1%	95.4%
3	16.3%	88.8%	3.7%	99.1%
4	7.4%	96.2%	0.7%	99.9%
5	2.7%	98.9%	0.1%	100.0%
6	0.8%	99.7%	0.0%	100.0%
7	0.2%	99.9%	0.0%	100.0%
8	0.0%	100.0%	0.0%	100.0%
9	0.0%	100.0%	0.0%	100.0%

	KSC181700V-1		KRP16BSV	
n # of failures	P(n)	P(n<,= r)	P(n)	P(n<,= r)
0	8.3%	8.3%	11.2%	11.2%
1	20.7%	29.0%	24.6%	35.8%
2	25.7%	54.7%	26.8%	62.7%
3	21.3%	76.0%	19.6%	82.2%
4	13.3%	89.3%	10.7%	92.9%
5	6.6%	95.9%	4.7%	97.6%
6	2.7%	98.6%	1.7%	99.3%
7	1.0%	99.6%	0.5%	99.8%
8	0.3%	99.9%	0.1%	100.0%
9	0.1%	100.0%	0.0%	100.0%

APPENDIX E

MATHEMATICAL MODEL OF HISTORICAL FAILURE DATA

Legend:

Part Number = Bearing Part Number
MTBF = Historical Mean Time Between Failure (in hours)
Failure Rate = Number of failures per hour
exp fails/yr = Number of expected failures per year
Unit Cost = Unit cost of the bearing
TPC = Total bearing parts cost per year
Mnrh Cost/exp maint/yr = Man-hour cost per expected maintenance action per year
TRC/yr = Total replacement cost per year (summation of parts cost and man-hour cost)
SDLM Costs = Parts cost for two SDLM replacements

Part Number	MTBF	Failure Rate	#exp fails/yr	Unit Cost	TPC/yr	Mnhr Cost/exp maint/yr	TRC/yr	SDLM Costs
MS289134A	8,428	0.00012	6	$46.14	$276.84	$2,102.08	$2,378.92	$369.12
KP16BS-FS428	8,839	0.00011	6	$45.74	$274.44	$611.44	$885.88	$914.80
KMDB16-9	10,066	0.00010	5	$191.84	$959.20	$433.84	$1,393.04	$2,302.08
KMDB28-8	10,354	0.00010	5	$209.40	$1,047.00	$393.01	$1,440.01	$1,675.20
MS21230-6	10,658	0.00009	5	$11.24	$56.20	$818.48	$874.68	$44.96
MS21230-5	12,079	0.00008	5	$11.61	$58.05	$111.65	$169.70	$92.88
DAT62-78A4	20,132	0.00005	3	$654.54	$1,963.62	$1,117.06	$3,080.68	$1,309.08
REP4M6-4FS428	21,317	0.00005	3	$46.74	$140.22	$554.10	$694.32	$2,150.04
MS21232-6	25,884	0.00004	2	$10.34	$20.68	$844.39	$865.07	$20.68
MS21230-7	27,875	0.00004	2	$15.96	$31.92	$488.71	$520.63	$31.92
Totals			42		$4,828.17	$7,474.75	$12,302.92	$8,910.76

Spare parts needed (SP) per unit:

$SP/unit = L*t + z_{1-a}*(L*t)^{0.5}$

t =90 days per LORA DEFAULT DATA GUIDE, however, assume parts are purchased annually.
z_{1-a} is the value of the standard normal variate corresponding to the confidence level "a"

for a 90% spare availability probability, z_{1-a} is 1.28

Part Number	Number of spares needed	Cost of spares
MS289134A	3	$138.42
KP16BS-FS428	3	$137.22
KMDB16-9	2	$383.68
KMDB28-8	2	$418.80
MS21230-6	2	$22.48
MS21230-5	2	$23.22
DAT62-78A4	2	$1,309.08
REP4M6-4FS428	2	$93.48
MS21232-6	1	$10.34
MS21230-7	1	$15.96
	Total	$2,552.68

Remaining Life Cycle Costs (assuming no change in costs)

Total $cost of fleet replacements and spares (per year)	$7,380.85
Total "O" level maintenance costs per year (Parts&Labor)	$14,855.60
Remaining Life Cycle costs (including 2 SDLM Periods)	$231,745

APPENDIX F

MATHEMATICAL MODEL OF EXPECTED FAILURE DATA

Legend:

Part Number = Bearing Part Number
MTBF = Historical Mean Time Between Failure (in hours)
Failure Rate = Number of failures per hour
exp fails/yr = Number of expected failures per year
Unit Cost = Unit cost of the bearing
MC/exp mt/yr = Man-hour cost per expected maintenance action per year
TPC/yr = Total parts cost per year
TRC/yr = Total replacement cost per year (summation of parts cost and man-hour cost)
SDLM Costs = Parts cost for one SDLM replacement

Current Part Number	New Part Number	MTBF	Failure Rate	#exp fails/yr	Unit Cost	MC/exp mt/yr	TPC/yr	TRC/yr	SDLM Costs
DAT62-78A4	KSC230162 RM	60,396	0.000017	2	$396.15	$744.93	$792.30	$1,537.23	$396.15
KMDB16-9	KSC181700 V-2	30,198	0.000033	3	$142.25	$260.59	$426.75	$687.34	$853.50
KMDB28-8	KSC181700 V-1	31,062	0.000032	3	$169.15	$235.80	$507.45	$743.25	$182.96
KP16BS-FS428	KRP16BSV	26,517	0.000038	3	*$45.74*	$305.47	$137.22	$442.69	$457.40
MS21230-5	KSC231005 V	36,237	0.000028	2	$52.30	$372.02	$104.60	$476.62	$209.20
MS21230-6	KSC231006 V	31,974	0.000031	3	$50.10	$491.04	$150.30	$641.34	$131.90
MS21230-7	KSC231307 V	83,625	0.000012	1	$65.95	$244.29	$65.95	$310.24	$65.95
MS21232-6	KSC231206 V	77,652	0.000013	1	$66.00	$422.26	$66.00	$488.26	$66.00
MS289134 A		25,284	0.000040	3	*$46.14*	$1,051.07	$138.42	$1,189.49	$46.14
REP4M6-4FS428	MS21151-8C	63,951	0.000016	2	*$46.74*	$369.34	$93.48	$462.82	$1,075.02
TOTALS				23		$4,496.82	$2,482.47	$6,979.29	$3,484.22

New Part Numbers	New Reliability	Current Reliability	% imp
KSC230162RM	0.96	0.87	9.83%
KSC181700V-2	0.91	0.76	20.13%
KSC181700V-1	0.92	0.77	18.87%
KRP16BSV	0.90	0.73	23.49%
KSC231005V	0.93	0.8	15.86%
KSC231006V	0.92	0.77	19.17%
KSC231307V	0.97	0.91	6.34%
KSC231206V	0.97	0.90	7.25%
TBA	0.90	0.72	24.58%
MS21151-8C	0.96	0.88	8.85%

Spare parts required (SP) per unit:

$$SP/unit = L*t + z_{1-a}*(L*t)^{0.5}$$

z_{1-a} is the value of the standard normal variate corresponding to the confidence level "a" . For a 90% spare availability probability, z_{1-a} is 1.28

Part Number	**Spares Required**	**Total Cost of Spares**
KSC230162RM	1	$396.15
KSC181700V-2	1	$142.25
KSC181700V-1	1	$169.15
KRP16BSV	1	$45.74
KSC231005V	1	$52.30
KSC231006V	1	$50.10
KSC231307V	1	$65.95
KSC231206V	1	$66.00
	1	$46.14
MS21151-8C	1	$46.74
TOTAL		$1,080.52

Remaining Life Cycle Costs (assuming no change in costs)

Total $ parts cost of fleet replacements and spares (per year) $3,562.99

Total "O" level maintenance replacement costs (parts & man-hours) per year

$6,979.29

Remaining Life Cycle Costs (including 1 SDLM Period)

$108,173.50

% reduction in life cycle cost (attributable to control bearing maintenance)
49%

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